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Materials used as PCM in thermal energy storage in buildings: A review

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ABSTRACT

In recent years the use of thermal energy storage with phase change materials has become a topic with a lot of interest within the research community, but also within architects and engineers. Many publications have appeared, and several books, but the information is disseminated and not very much organised. This paper shows a review of the latest publications on the use of phase change materials (PCM) in buildings. The paper compiles information about the requirements of the use of this technology, classification of materials, materials available and problems and possible solutions on the application of such materials in buildings.

Contents

1. Introduction

The use of storage in a building can smooth temperature fluctuation. Thermal energy storage in buildings can be implemented by sensible heat (increasing and decreasing the temperature of the building envelopes, for example), or by latent heat (with the inclusion of phase change materials – PCM – to increase thermal inertia). The main advantage of latent heat storage is the high storage density in small temperature intervals.

Latent storage can be used for heating and for cooling of buildings, and it can be incorporated as a passive system or also in active systems.

In recent years several reviews have appeared on this topic. Four books on the topic have appeared recently, one authored by Dinçer and Rosen in 2002 [1], a compilation edited by Hadorn in 2005 [2], another by Paksoy in 2007 [3], and another book authored by Mehling and Cabeza in 2008 [4].

The book written by Dinçer and Rosen [1] deals with thermal energy storage (TES) in general, being phase change materials

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(PCM) just a part of it, and not focused on the application in buildings. In the two compilations by Hadorn [2] and Paksoy [3], different TES technologies are studied, and PCM in buildings have a part on them [5–7]. Finally, the book by Mehling and Cabeza [4] gives a deep study of the PCM technology.

Several reviews have been published from 2003 to 2009 [8–15]. The first review was published on 2003 by Zalba et al. [8]. In this work, a review has been carried out of the history of thermal energy storage with solid–liquid phase change focusing in three aspects: materials, heat transfer, and applications. Materials used by researchers as potential PCM were described, together with their thermophysical properties. Commercial PCM were also listed. Different methods of thermal properties characterization can be found. Problems in long term stability of the materials and their encapsulation are discussed. Heat transfer is considered mainly from a theoretical point of view, by using different simulation techniques. Many applications of PCM can be found, divided in ice storage, building applications, conservation and transportation of temperature sensitive materials, water tanks vs. PCM tanks, and others.

In 2004, the research group leaded by M. Farid published two reviews about PCM, one of them focusing on building applications. The first paper [9] reviews previous work on latent heat storage and provides an insight to recent efforts to develop new classes of phase change materials for use in energy storage. Three aspects have been the focus of this review: PCM, encapsulation and applications. There are large numbers of phase change materials that melt and solidify at a wide range of temperatures, making them attractive in several applications. The main advantages of PCM encapsulation are providing large heat transfer area, reduction of the PCM reactivity towards the outside environment and controlling the changes in volume of the storage materials as phase change occurs. Different applications in which the phase change method of heat storage can be applied are also reviewed in this paper.

The other paper [10] summarizes the investigation and analysis of thermal energy storage systems incorporating PCM for use in building applications. Researches on thermal storage in which the PCM is encapsulated in concrete, gypsum wallboard, ceiling and floor have been ongoing for some time and are discussed. The problems associated with the application of PCM with regard to the selection of materials and the methods used to contain them are also discussed.

In 2007 Tyagi and Buddhi [11] published a comprehensive review of various possible methods for heating and cooling in buildings. The thermal performance of various types of systems like PCM trombe wall, PCM wallboards, PCM shutters, PCM building blocks, air-based heating systems, floor heating, ceiling boards, etc., is presented in this paper. It claims that all systems have good potential for heating and cooling in building through phase change materials and also very beneficial to reduce the energy demand of the buildings.

Also in 2007 a new review appeared, authored by Kenisarin and Mahkamov [12]. This paper looks at the current state of research in this particular field, with the main focus being on the assessment of the thermal properties of various PCM, methods of heat transfer enhancement and design configurations of heat storage facilities to be used as a part of solar passive and active space heating systems, greenhouses and solar cooking.

Finally, in 2009 three new reviews have appeared, where materials for PCM application in buildings are discussed. The first one is from Sharma et al. [13], and it summarizes the investigation and analysis of the available thermal energy storage systems incorporating PCM for use in different applications. This paper presents the current research in this particular field, being the main focus the assessment of thermal properties of various PCM. The heat storage applications presented are as a part of solar water-heating systems, solar air heating systems, solar cooking, solar green house, space heating and cooling application for buildings, off-peak electricity storage systems, and waste heat recovery systems. The paper also presents the melt fraction studies of the few identified PCM used in various applications for storage systems with different heat exchanger container materials.

Zhu et al. [14] did an overview of the previous research work on dynamic characteristics and energy performance of buildings due to the integration of PCM. Both active and passive systems are reviewed. Since the particular interest in using PCM for free cooling and peak load shifting, the specific research efforts on both subjects are reviewed separately. A few useful conclusive remarks and recommendations for future work are presented.

Wang et al. [15] present the concept of ideal energy-saving building envelope, which is used to guide the building envelope material selection and thermal performance design. This paper reviews some available researches on phase change building material and phase change energy storage building envelope. At last, this paper presents some current problems that need further research.

Here only the materials used, proposed and studied as potential phase change materials will be looked at. Also, only the applications for buildings should be considered in this paper, therefore the phase change temperature should be restricted to around 15–70 °C.

2. Classification

In 1983 Abhat [16] gave a useful classification of the substances used for thermal energy storage (Fig. 1). Another classification was given by Mehling and Cabeza in 1997 [6] (Fig. 2).

Several authors [4,8,15] have presented a comparison of the advantages and disadvantages of organic and inorganic materials, as shown in Tables 1 and 2.

3. Materials

Many substances have been studied as potential PCM, but only a few of them are commercialized as so. The books and reviews cited above [1–15] have presented different tables with substances, eutectics and mixtures (inorganic, organic and fatty acids), that have been studied by different researchers for their potential use as PCM (Tables 3–6).

Materials to be used for phase change thermal energy storage must have a large latent heat and high thermal conductivity. They should have a melting temperature lying in the practical range of operation, melt congruently with minimum subcooling and be chemically stable, low in cost, nontoxic and non-corrosive. Materials that have been studied during the last 40 years are salt hydrates, paraffin waxes, fatty acids and eutectics of organic and non-organic compounds [9].

According to [12], the following phase change material (PCM) properties to be used for latent heat storage were highlighted as desirable:

Table 1
Comparison of organic and inorganic materials for heat storage [4,8].

	Organic	Inorganic
Advantages	No corrosives	Greater phase change enthalpy
	Low or none subcooling	
	Chemical and thermal stability	
Disadvantages	Lower phase change enthalpy	Subcooling
	Low thermal conductivity	Corrosion
	Flammability	Phase separation
		Phase segregation, lack of thermal stability

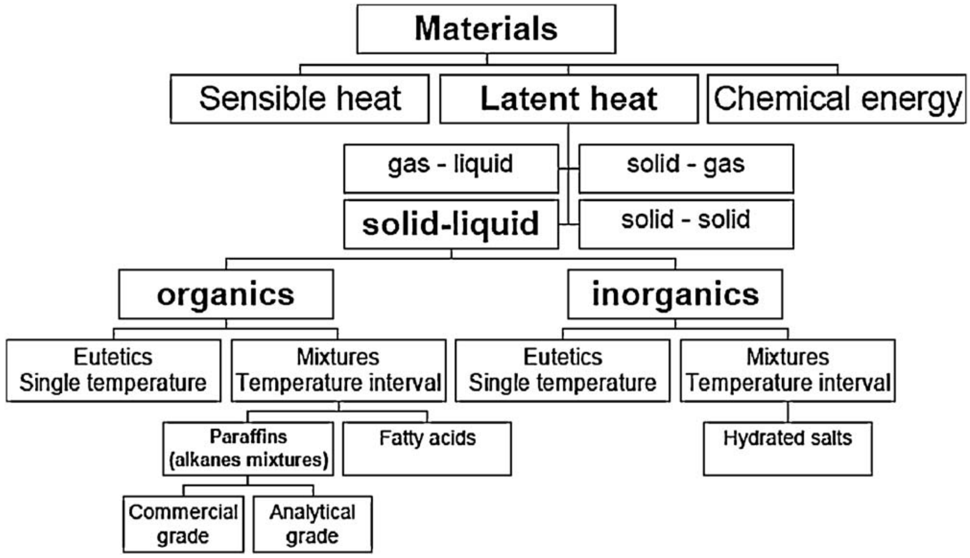


Fig. 1. Classification of energy storage materials [2,8,16].

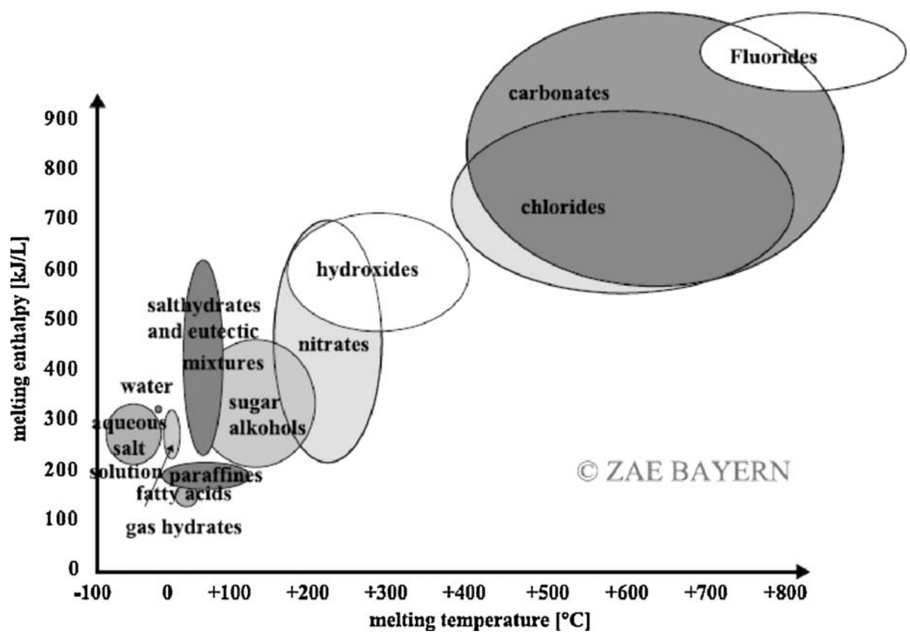


Fig. 2. Classes of materials that can be used as PCM with regard to their typical range of melting temperature and melting enthalpy (graph: ZAE Bayern) [4,6].

1. a high value of the heat of fusion and specific heat per unit volume and weight,
2. a melting point which matches the application,
3. a low vapour pressure (<1 bar) at the operational temperature,
4. a chemical stability and non-corrosiveness,
5. not be hazardous, highly inflammable or poisonous,
6. a reproducible crystallisation without degradation,
7. a small subcooling degree and high rate of crystal growth,

Table 2
Classification and properties of PCM, as presented in [15].

Classification	Inorganic	Organic
Category	Crystalline hydrate, molten salt, metal or alloy	High aliphatic hydrocarbon, acid/esters or salts, alcohols, aromatic hydrocarbons, aromatic ketone, lactam, freon, multi-carbonated category, polymers
Advantages	Higher energy storage density, higher thermal conductivity, non-flammable, inexpensive	Physical and chemical stability, good thermal behaviour, adjustable transition zone
Disadvantages	Subcooling, phase segregation, corrosive	Low thermal conductivity, low density, low melting point, highly volatile, flammable, volume change
Methods for improvement	Mixed with nucleating and thickening agents, thin layer arranged horizontally, mechanical stir	High thermal conductivity additives, fire-retardant additives

Table 3
Thermophysical properties of materials for cooling applications (melting temperature up to 21 °C).

Material	Type	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m K)	Density (kg/m^3)
$Al(NO_3)_3$ (30.5 wt%) + H_2O	Eutectic water–salt solution	−30.6 [4]	131 [4]	–	1283 (liquid)
					1251 (solid)
NaCl (22.4 wt%) + H_2O	Eutectic water–salt solution	−21.2 [4]	222 [4]	–	1165 (liquid)
					1108 (solid)
KCl (19.5 wt%) + H_2O	Eutectic water–salt solution	−10.7 [4]	283 [4]	–	1126 (liquid)
					1105 (solid)
Diethylene glycol	Eutectic Organic	−10 to −7 [4]	247 [4]	–	1200 (liquid)
Dodecane	Organic	−9.6 [12]	216 [12]	2.21 (liquid)	–
Triethylene glycol	Organic	−7 [4]	247 [4]	–	1200 (liquid)
Tetradecane + octadecane	Eutectic Organic	−4.02 [12]	227.52 [12]	–	–
H_2O		0 [4]	333 [4]	0.6 (liquid)	998 (liquid, 20 °C)
				2.2 (solid)	917 (solid, 0 °C)
		0 [6]	333 [6]	0.612	998 (liquid, 20 °C)
				.	917 (solid, 0 °C)
		0 [8]	334 [8]	0.61	996 (solid, 30 °C)
H_2O + polyacrylamida	Compound	0 [8]	295 [8]	0.486	1047 (liquid)
91.67% tetradecane + 8.33% hexadecane	Eutectic Organic	1.7 [12]	156.2 [12]	–	–
Tetradecane + docosane	Eutectic Organic	1.5–5.6 [12]	234.33 [12]	–	–
Tetradecane + geneicosane	Eutectic Organic	3.54–5.56 [12]	200.28 [12]	–	–
Tetrahidrofurano (THF)	Eutectic Organic	5 [4]	280 [4]	–	970 (solid)
Paraffin C_{14}	Organic	5.5 [13]	228 [13]	–	–
		4 [6]	153 [6]		
		4.5 [8]	165 [8]		
n-Tetradecane	Organic	6 [8]	230 [8]		–
		5.8–5.9 [12]	258–227 [12]	0.210 (solid)	
Pentadecane + heneicosane	Eutectic Organic	6.23–7.21 [12]	128.25 [12]	–	–
Formic acid	Fatty acid	7.8 [12]	247 [12]	–	–
$LiClO_3{\cdot}3H_2O$	Inorganic (salt hydrate)	8 [6,8]	253 [6,8]	–	1720 (solid)
		8 [4,11]	155 [4,11]		1530 (liquid)
Polyglycol E400	Organic	8 [1,8]	99.6 [1,8]	0.187 (liquid, 38.6 °C)	1125 (liquid, 25 °C)
					1228 (solid, 24 °C)
		8 [4]	100 [4]	0.19	1228 (solid)
Paraffin C_{15}–C_{16}	Organic	8 [6,8]	153 [6,8]	–	–
Pentadecane + octadecane	Eutectic Organic	8.5–9.0 [12]	271.93 [12]	–	–
Pentadecane + docosane	Eutectic Organic	7.6–8.99 [12]	214.83 [12]	–	–
$ZnCl_2{\cdot}3H_2O$	Inorganic (salt hydrate)	10 [8]	–	–	–
Paraffin C_{15}	Organic	10 [13]	205 [13]	–	–
n-Pentadecane	Organic	10 [8]		–	770 (liquid)
		9.9 [12]	193.9 [12]		
Tetrabutyl ammoniumbromide (type A–type B)	Organic	10–12 [4]	193–199 [4]	–	–
Isopropyl palmitate	Organic	11 [8]	95–100 [8]	–	–
$K_2HPO_4{\cdot}6H_2O$	Inorganic (salt hydrate)	13 [8]		–	–
		14 [13]	109 [13]		
90% capric acid + 10% lauric acid	Organic	13.3 [8]	142.2 [8]	–	–
38.5% triethylolethane + 31.5% water + 30% urea	Organic eutectic	13.4 [13]	160 [13]	–	–
Isopropyl stearate	Organic	14–18 [8]	140–142 [8]	–	–
38.5% trimethyloletane + 31.5% water + 30% urea	Organic mixture	14.4 [12]	160 [12]	0.66	1170 (liquid)
55% $CaCl_2{\cdot}6H_2O$ + 55% $CaBr_2{\cdot}6H_2O$	Inorganic eutectic	14.7 [13]	140 [13]	–	–
NaOH·(3/2)H_2O	Inorganic (salt hydrate)	15 [8]	–	–	–
		15.4 [8]			
$Mn(NO_3){\cdot}6H_2O$ + $MgCl_2{\cdot}6H_2O$	Inorganic mixture	15–25 [12]	125.9 [12]	–	1738 (liquid, 20 °C)
Propyl palmitate	Organic	16–19 [4,10]	186 [4,8,10]	–	–
		10 [4,8]			
Caprylic acid	Fatty acid	16 [1,4,6,8]	148.5 [1,4,6,8]	0.149	901 (liquid, 30 °C)
		16.3 [4,6,8,13]	149 [4,6,8,13]		981 (solid, 13 °C)
Dimethyl sulfoxide (DMSO)	Organic	16.5 [4,8]	85.7 [4,8]	–	1009 (liquid)
Paraffin C_{16}	Organic	16.7 [13]	237.1 [13]	–	–
Acetic acid	Fatty acid	16.7 [8]	184 [8]	–	–
45% capric acid + 55% lauric acid	Organic	17–21 [12]	143 [12]	–	–
		21 [4,8]	143 [4,8]		
48% butyl palmite + 48% butyl stearate + 3% other	Organic mixture	17 [12]	140 [12]	–	–
45–52% $LiNO_3{\cdot}3H_2O$ + 48–55% $Zn(NO_3)_2{\cdot}6H_2O$	Inorganic mixture	17.2 [4]	220 [4]	–	–
Glycerin	Organic	17.9 [13]	198.7 [13]	0.143	–
Capric acid + lauric acid	Fatty acid mixture	18 [12]	120 [12]	0.143	–

Table 4
Thermophysical properties of materials for comfort applications in buildings (between 22 and 28 °C).

Material	Type	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m K)	Density (kg/m^3)
n-Heptadecane	Organic	19 [8] 20.8–21.7 [12]	240 [8] 171–172 [12]	0.21	760 (liquid)
61.5 mol% capric acid + 38.5 mol% lauric acid	Fatty acid mixture	19.1 [12]	132 [12]	–	–
Butyl stearate	Organic	19 [4,6,8,11] 18–23 [4,6,10]	140 [4,6,8,11] 123–200 [4,6,10]	 0.21	760 (liquid)
Paraffin C_{16}–C_{18}	Organic	20–22 [4,6,8,11]	152 [4,6,8,11]	–	–
$FeBr_3 \cdot 6H_2O$	Inorganic (salt hydrate)	21 [13] 27 [13]	105 [13]	–	–
Capric acid + lauric acid	Fatty acid mixture	21 [11]	143 [11]	–	–
Dimethyl sabacate	Organic	21 [4,8,11]	120–135 [4,8,11]	–	–
Octadecyl 3-mencaptopropylate	Organic	21 [4]	143 [4]	–	–
26.5% myristic acid + 73.5% capric acid	Fatty acid mixture	21.4 [12]	152 [12]	–	–
Paraffin C_{17}	Organic	21.7 [13]	213 [13]	–	–
Polyglycol E600	Organic	22 [1,4,8,11] 17–22 [4] 20–25 [13]	127.2 [1,4,8,11] 127 [4] 146 [13]	0.1897 (liquid, 38.6 °C) 0.19 (liquid)	1126 (liquid, 25 °C) 1232 (solid, 4 °C)
65–90% methyl palmitate + 35–10% Methyl stearate	Organic mixture	22–25.5 [12]	120 [12]	–	–
Paraffin C_{13}–C_{24}	Organic	22–24 [4,8,11]	189 [4,8,11]	0.21 (liquid)	0.760 (liquid) 0.900 (solid)
75.2% capric acid + 24.8% palmitic acid	Fatty acid mixture	22.1 [12]	153 [12]	–	–
Ethyl palmitate	Organic mixture	23 [12]	122 [12]	–	–
34% $C_{14}H_{28}O_2$ + 66% $C_{10}H_{20}O_2$	Organic eutectic	24 [13]	147.7 [13]	–	–
55–65% $LiNO_3 \cdot 3H_2O$ + 35–45% $Ni(NO_3)_2$	Inorganic mixture	24.2 [4]	230 [4]	–	–
45% $Ca(NO_3)_2 \cdot 6H_2O$ + 55% $Zn(NO_3)2 \cdot 6H_2O$	Inorganic mixture	25 [4]	130 [4]	–	1930
66.6% $CaCl_2 \cdot 6H_2O$ + 33.3% $MgCl_2 \cdot 6H_2O$	Inorganic mixture	25 [4,8,11]	127 [4,8,11]	–	1590
50% $CaCl_2$ + 50% $MgCl_2$ + $6H_2O$	Inorganic eutectic	25 [13]	95 [13]	–	–
Octadecane + docosane	Organic eutectic	25.5–27.0 [12]	203.8 [12]	–	–
$Mn(NO_3) \cdot 6H_2O$	Inorganic (salt hydrate)	25.5 [4,11,13] 25.8 [4,8]	125.9 [4,11] 125.9 [4,8] 148 [13]	–	1738 (liquid, 20 °C) 1728 (liquid, 40 °C) 1795 (liquid, 5 °C)
Octadecane + heneicosane	Eutectic Organic	25.8–26.0 [12]	173.93 [12]	–	–
Lactic acid	Fatty acid	26 [13]	184 [13]	–	–
Octadecyl thioglyate	Organic	26 [4]	90 [4]	–	–
34% myristic acid + 66% capric acid	Organic	26 [4,11] 24 [4,8]	147.7 [4,11] 147.7 [4,8]	–	–
1-Dodecanol	Organic	26 [8,11] 17.5–23.3 [4,10]	200 [8,11] 188.8 [4,10]	–	–
48% $CaCl_2$ + 4.3% NaCl + 0.4% KCl + 47.3% H_2O	Inorganic mixture	26.8 [4,8,11]	188 [4,8,11]	–	1640
86.6% capric acid + 13.4% stearic acid	Fatty acid mixture	26.8 [12]	160 [12]	–	–
50% CH_3CONH_2 + 50% NH_2CONH_2	Organic eutectic	27 [13]	163 [13]		
4.3% NaCl + 0.4% KCl + 48% $CaCl_2$ + 47.3% H_2O	Inorganic mixture	27 [4,6]	188 [4,6]	–	1530 (liquid) 1640 (solid)
Vinyl stearate	Organic	27–29 [4,8,11] 27 [4]	122 [4,8,11]	–	–
Paraffin C_{18}	Organic	28 [4,6,8,11,13] 27.5–22.5 [4]	244 [4,6,8,11,13] 243.5 [4]	0.148 (liquid) 0.15 (solid)	0.774 (liquid) 0.814 (solid)
n-Octadecane	Organic	28 [8] 28–28.1 [12]	200 [8] 245 [8] 250–247.7 [12]	0.148 (liquid) 0.358 (solid) 0.358 (solid)	774 (liquid) 814 (solid) 779 (liquid)

8. a small volume variation during solidification,
9. a high thermal conductivity, and
10. availability and abundance.

Here only melting temperatures reasonable for building applications are included. Some of their thermophysical properties are included (melting point, heat of fusion, thermal conductivity and density), although some authors give further information (congruent/incongruent melting, volume change, specific heat, etc.). A list of the commercial PCM found in the reviewed literature, with their thermophysical properties as given by the companies (melting point, heat of fusion and density), and the company that is producing them is also presented (Tables 7–9 and Figs. 3 and 4).

Some substances such as salt hydrates, paraffin and paraffin waxes, fatty acids and other compounds, have the required high latent heat of fusion in the temperature range from 0 to 150 °C and these materials could be used for solar applications, though have certain shortcomings [12].

The paraffins are a mixture of pure alkanes which have quite a wide range of the phase change temperature. These paraffins also have low thermal conductivity compared to inorganic materials, and therefore the choice of those which can be used for practical solar applications is very limited [12].

Commercial paraffin waxes are cheap with moderate thermal storage densities (~200 kJ/kg or 150 MJ/m^3) and a wide range of melting temperatures [9]. They undergo negligible subcooling and are chemically inert and stable with no phase segregation. However, they have low thermal conductivity (~0.2 W/m °C), which limits their applications.

The main limitation of salt hydrates is their chemical instability when they are heated, as at elevated temperatures they degrade, losing some water content every heating cycle. Furthermore, some

Table 5
Thermophysical properties of materials for hot water applications (between 29 and 60 °C).

Material	Type	Melting temperature (°C)	Heat of Fusion (kJ/kg)	Thermal conductivity (W/m K)	Density (kg/m³)
$CaCl_2·6H_2O$	Inorganic (salt hydrate)	29 [1,4,8,11]	190.8 [1,4,8,11]	0.540 (liquid, 38.7 °C)	1562 (liquid, 32 °C)
		29 [6]	171–192 [6]	0.540–1.088 (liquid–solid)	
		29.2 [4,8]	171 [4,8]	0.561 (liquid, 61.2 °C)	1496 (liquid)
		29.6 [4,8]	174.4 [4,8]	1.088 (liquid, 23 °C)	1802 (liquid, 24 °C)
		29.7 [4,8,10]	192 [4,8,10]		1710 (liquid, 25 °C)
		30 [4,8]	296 [4,8]		1634
		29–39 [8]			1620
Methyl stearate	Organic mixture	29 [12]	169 [12]	–	–
62.5% Trimethyloletane + 37% water	Organic mixture	29.8 [12]	218 [12]	0.65	1120
$CaCl_2·12H_2O$	Inorganic (salt hydrate)	29.8 [13]	174 [13]	–	–
Ga + [Ga-NH_4]	Inorganic eutectic	29.8 [13]	–	–	–
Ga	Inorganic eutectic	30 [13]	80.9 [13]	–	–
$LiNO_3·3H_2O$	Inorganic (salt hydrate)	30 [4,6,8,11,13]	296 [4,6,8,11]	–	–
			189 [13]		
$LiNO_3·2H_2O$	Inorganic (salt hydrate)	30 [13]	296 [13]	–	–
67% $Ca(NO_3)_2$ + 33% $Mg(NO_3)_2$	Inorganic mixture	30 [4]	136 [4]	–	1670
47% $Ca(NO_3)_2·4H_2O$ + 53% $Mg(NO_3)_2·6H_2O$	Inorganic eutectic	30 [8,11]	136 [8,11]	–	–
60% $Na(CH_3COO)·3H_2O$ + 40% $CO(NH_2)_2$	Inorganic eutectic	31.5 [4,8]	226 [4,8]	–	–
		30 [4,8,11,13]	200.5 [4,8,11,13]		
$Na_2SO_4·3H_2O$	Inorganic (salt hydrate)	32 [4]	251 [4]	–	–
		32.4 [13]	241 [13]		
$Na_2SO_4·10H_2O$	Inorganic (salt hydrate)	31–32 [8]			
		32 [4,8,11]	254 [4,8]	0.554 (solid)	1485 (solid)
			251.1 [8]		1458
			251 [11]		
		32.4 [8]		0.554	1485
$Na_2CO_3·10H_2O$	Inorganic (salt hydrate)	32–36 [8]	246.5 [8]	–	1442
		33 [8]	247 [8]		
		32 [13]	267 [13]		
Paraffin C_{19}	Organic	32 [13]	222 [13]	–	–
Capric acid	Fatty acid	32 [1,8,11]	152.7 [1,8,11]	0.153	878 (liquid, 45 °C)
		30.1–31.4 [12]	150–158 [12]		
		31.5 [8]	153 [4,6,8]	0.152–0.149 (liquid)	886–1004
		32 [4,6]		0.149	1004 (solid, 24 °C)
		36 [8]	152 [8]		
62.6% lauric acid + 37.4% myristic acid	Fatty acid mixture	32.6 [12]	156 [12]	–	–
64% lauric acid + 36% palmitic acid	Fatty acid mixture	32.8 [12]	165 [12]	–	–
80% lauric acid + 20% palmitic acid	Fatty acid mixture	32.7 [12]	150.6 [12]	–	–
77% lauric acid + 23% palmitic acid	Fatty acid mixture	33 [12]	150.6 [12]	–	–
Lauric acid + stearic acid	Fatty acid mixture	34 [12]	150 [12]	–	–
$CaBr_2·6H_2O$	Inorganic (salt hydrate)	34 [1,8]	115.5 [1,8]	–	1956 (liquid, 35 °C)
		34 [13]	138 [13]		2194 (solid, 24 °C)
$LiBr_2·2H_2O$	Inorganic (salt hydrate)	34 [13]	124 [13]	–	–
66% lauric acid + 34% myristic acid	Organic	34.2 [12]	166.8 [12]	–	–
$Na_2HPO_4·12H_2O$	Inorganic (salt hydrate)	35–44 [4,6]	280 [4,6]	0.514 (solid)	1522 (solid)
		35 [8]	281 [8]		
		35.2 [8]			
		35.5 [8]	265 [8]		
		36 [8]	280 [8]		
		40 [13]	279 [13]		
Polyglycol E1000	Organic	35–40 [4]	–	–	–
69% lauric acid + 31% palmitic acid	Fatty acid mixture	35.2 [12]	166.3 [12]	–	–
$Zn(NO_3)_2·6H_2O$	Inorganic (salt hydrate)	36 [1,8]	146.9 [1,8]	0.464 (liquid, 39.9 °C)	1828 (liquid, 36 °C)
					1937 (solid, 24 °C)
		36.4 [8]	147 [8]	0.469 (liquid, 61.2 °C)	2065 (solid, 14 °C)
		45.5 [4]			
		36.1 [13]	134 [13]		

Table 5 (*Continued*)

Material	Type	Melting temperature (°C)	Heat of Fusion (kJ/kg)	Thermal conductivity (W/m K)	Density (kg/m^3)
Paraffin C_{20}	Organic	36.7 [13]	246 [13]	–	–
$FeCl_3 \cdot 6H_2O$	Inorganic (salt hydrate)	37 [8]	223 [8]	–	–
$Mn(NO_3) \cdot 6H_2O$	Inorganic (salt hydrate)	37.1 [13]	115 [13]	–	1738 (liquid, 20 °C)
					1795 (liquid, 5 °C)
1-Tetradecanol	Organic	38 [8]	205 [8]	–	–
Methyl palmitate	Organic	38 [12]	205 [12]	–	–
		29 [13]			
51% mystiric acid + 49% palmitic acid	Organic	39.8 [13]	174 [13]	–	–
Heneicosane	Organic	40–40.2 [12]	155.5–213 [12]	–	778 (solid)
Paraffin C_{21}	Organic	40.2 [13]	200 [13]	–	–
50% $Na(CH_3COO) \cdot 3H_2O$ + 50% $HCONH_2$	Organic eutectic	40.5 [8]	255 [8]	–	–
$CoSO_4 \cdot 7H_2O$	Inorganic (salt hydrate)	40.7 [13]	170 [13]	–	–
Phenol	Organic	41 [13]	120 [13]	–	–
Heptadecanone	Organic	41 [13]	201 [13]	–	–
1-Cyclodecyloctadecane	Organic	41 [13]	218 [13]	–	–
4-Heptadecanone	Organic	41 [13]	197 [13]	–	–
$KF \cdot 2H_2O$	Inorganic (salt hydrate)	41.4 [8]		–	–
		42 [13]	162 [13]		
$MgI_2 \cdot 8H_2O$	Inorganic (salt hydrate)	42 [13]	133 [13]	–	–
$CaI_2 \cdot 6H_2O$	Inorganic (salt hydrate)	42 [13]	162 [13]	–	–
$CaI_2 \cdot 6H_2O$	Inorganic (salt hydrate)	42 [13]	162 [13]	–	–
$K(CH_3COO) \cdot (1/2) H_2O$	Inorganic (salt hydrate)	42 [8]	–	–	–
Lauric acid	Fatty acid	42–44 [4,6]	178 [4,6]	0.147	870(liquid)
		42–43 [8]	120–126 [8]		
		43.7 [12]	210.8 [12]	0.160	1007 (solid)
		49 [14]	178 [14]		
Paraffin C_{16}–C_{28}	Organic	42–44 [8]	189 [8]	0.21	0.765 (liquid) 0.910 (solid)
59% mystiric acid + 41% palmitic acid	Fatty acid mixture	42.6 [13]	169.2 [13]	–	–
$Ca(NO_3)_2 \cdot 4H_2O$	Inorganic (salt hydrate)	42.7 [4,8]	–	–	–
		47 [4,13]	153 [13]		
65.7% mystiric acid + 34.7% stearic acid	Fatty acid mixture	44 [13]	181 [13]	–	–
64% mystiric acid + 36% stearic acid	Fatty acid mixture	44 [13]	182 [13]	–	–
Paraffin C_{22}	Organic	44 [13]	249 [13]	–	–
Docosane	Organic	44 [12]	196.5–252 [12]	–	–
$K_2HPO_4 \cdot 7H_2O$	Inorganic (salt hydrate)	45 [13]	145 [13]	–	–
$K_3(PO_4) \cdot 7H_2O$	Inorganic (salt hydrate)	45 [4,8]	–	–	–
$Zn(NO_3)_2 \cdot 4H_2O$	Inorganic (salt hydrate)	45.5 [8]		–	–
		47 [8]			
		45 [13]	110 [13]		
53% NH_2CONH_2 + 47% NH_4NO_3	Inorganic eutectic	46 [13]	95 [13]	–	–
$Mg(NO_3) \cdot 2H_2O$	Inorganic (salt hydrate)	47 [13]	142 [13]	–	–
$Fe(NO_3)_2 \cdot 9H_2O$	Inorganic (salt hydrate)	47 [13]	155 [13]	–	–
Eladic acid	Fatty acid	47 [13]	218 [13]		
Paraffin C_{23}	Organic	47.5 [13]	232 [13]	–	–
$Na_2HPO_4 \cdot 7H_2O$	Inorganic (salt hydrate)	48 [4]	–	–	–
$Na_2SiO_3 \cdot 4H_2O$	Inorganic (salt hydrate)	48 [13]	168 [13]	–	–
$K_2HPO_4 \cdot 3H_2O$	Inorganic (salt hydrate)	48 [13]	99 [13]	–	–
$Na_2S_2O_3 \cdot 5H_2O$	Inorganic (salt hydrate)	48 [4,8]	201 [4,8]	–	1600 (solid)
		48–49 [4,8]	209.3 [4,8]		1666 (solid)
		48–55 [4,6]	187–209 [4,6]		1670 (liquid)
		48 [12]	201–206 [12]		1750 (solid)
		48.5 [13]	210 [13]		
3-Heptadecanone	Organic	48 [13]	218 [13]	–	–
2-Heptadecanone	Organic	48 [13]	218 [13]	–	–
Paraffin C_{20}–C_{33}	Organic	48–50 [4,8]	189 [4,8]	0.21	0.769 (liquid) 0.912 (solid)

Table 5 (*Continued*)

Material	Type	Melting temperature (°C)	Heat of Fusion (kJ/kg)	Thermal conductivity (W/m K)	Density (kg/m^3)
$MgSO_4 \cdot 7H_2O$	Inorganic (salt hydrate)	48.5 [4,8]	202 [4,8]	–	–
Myristic acid	Organic	49–51 [4,6,8]	204.5 [4,6,8]		861 (liquid)
		58 [4,6,8]	186–204 [4,6,8]	0.17 (solid)	990 (solid)
		58 [13]	199 [13]		
		54 [4,8]	187 [4,8]		844 (solid)
Cetyl alcohol	Organic	49.3 [13]	141 [13]	–	–
64.9% palmitic acid + 35.1% stearic acid	Fatty acid mixture	50.4 [13]	181 [13]	–	–
Palmitic acid + stearic acid	Fatty acid mixture	51 [13]	160 [13]	–	–
Palmitic acid + stearic acid + other fatty acid	Fatty acid mixture	51–56 [13]	180 [13]	–	–
27.5% palmitic acid + 65% stearic acid + other fatty acids	Organic mixture	51–56 [12]	180 [12]	–	–
9-Heptadecanone	Organic	51 [13]	213 [13]	–	–
$Ca(NO_3)_2 \cdot 3H_2O$	Inorganic (salt hydrate)	51 [13]	104 [13]	–	–
61.5% $Mg(NO_3)_2$ + 38.5% NH_4NO_3	Inorganic mixture	52 [4,8,13]	125.5 [4,8,13]	0.494 (65 °C)	1515
				0.515 (88 °C)	1596
				0.552 (36 °C)	
64.2% palmitic acid + 35.8% stearic acid	Fatty acid mixture	52.3 [13]	181.7 [13]	–	–
Pentadecanoic acid	Fatty acid	52.5 [13]	178 [13]	–	–
37.5% urea + 63.5% acetamide	Organic	53 [4,8]	–	–	–
$Zn(NO_3)_2 \cdot 2H_2O$	Inorganic (salt hydrate)	54 [4,8]	–	–	–
		55 [13]			
Polyglycol E10000	Organic	55–66 [4]	–	–	–
$Mg(NO_3)_2 \cdot 6H_2O/Mg(NO_3)_2 \cdot 2H_2O$	Inorganic (salt hydrate)	55.5 [4,8]	–	–	–
$FeCl_3 \cdot 2H_2O$	Inorganic (salt hydrate)	56 [13]	90 [13]	–	–
Tristearin	Organic	56 [13]	191 [13]	–	–
Paraffin C_{26}	Organic	56.3 [13]	256 [13]	–	–
$Ni(NO_3)_2 \cdot 6H_2O$	Inorganic (salt hydrate)	57 [13]	169 [13]	–	–
$NaOH \cdot H_2O$	Inorganic (salt hydrate)	58 [4,8]	–	–	–
$MnCl_2 \cdot 4H_2O$	Inorganic (salt hydrate)	58 [13]	151 [13]	–	–
$MgCl_2 \cdot 4H_2O$	Inorganic (salt hydrate)	58 [13]	178 [13]	–	–
$Na(CH_3COO) \cdot 3H_2O$	Inorganic (salt hydrate)	58 [4,6,8]	226–264 [4,6,8]	0.63	1280 (liquid)
		58.4 [4,8]			1280–1450
		58 [12,13]	267 [12]		1450 (solid)
			265 [12,13]		1450 (solid)
50% $Mg(NO_3)_2 \cdot 6H_2O$ + 50% $MgCl_2 \cdot 6H_2O$	Inorganic eutectic	58–59 [4,6]	132 [4,6]	0.510 (liquid)	1550 (liquid) 1630 (solid)
		59.1 [13]	144 [13]	0.680 (solid)	
62.5% $Mg(NO_3)_2$ + 37.5% NH_4NO_3	Inorganic mixture	58 [12]	267 [12]	0.63 (solid)	1.45
58.7% $Mg(NO_3)_2 \cdot 6H_2O$ + 41.3% $MgCl_2 \cdot 6H_2O$	Inorganic eutectic	59 [4,8]	132.2 [4,8]	0.510 (65 °C)	1550
				0.565 (85 °C)	1630
				0.678 (38 °C)	1680
		58 [4,8]	132 [4,8]	0.34 (solid)	
		59.1 [4]	144 [4]		
		58.0–58.3 [12]	120–132 [12]		
Paraffin C_{22}–C_{45}	Organic	58–60 [4,8]	189	0.21	0.795 (liquid)
					0.920 (solid)
Paraffin C_{27}	Organic	58.8 [13]	236	–	–
$Cd(NO_3)_2 \cdot 4H_2O$	Inorganic (salt hydrate)	59.5 [4,8]	–	–	–
80% $Mg(NO_3)_2 \cdot 6H_2O$ + 20% $MgCl_2 \cdot 6H_2O$	Inorganic (salt hydrate)	60 [4]	150	–	–
$Fe(NO_3)_2 \cdot 6H_2O$	Inorganic (salt hydrate)	60 [4,8]		–	–
		60.5 [13]	126 [13]		
11% palmitic acid + 83% stearic acid + other fatty acids	Fatty acid mixture	60–66 [12]	206 [12]	–	–

salts are chemically aggressive towards structural materials and they have low heat conductivity. Finally, salt hydrates have a relatively high degree of supercooling [12].

Salt hydrates are attractive materials for use in thermal energy storage due to their high volumetric storage density (~350 MJ/m^3), relatively high thermal conductivity compared to organic materials (~0.5 W/m °C), and moderate costs compared to paraffin waxes, with few exceptions [9].

According to [6,12], the main supply companies in the market of phase change heat and cold storage materials include Cristopia (France), TEAP Energy (Australia), Rubitherm GmbH (Germany), EPS Ltd. (UK), PCM Thermal Solutions (USA), Climator (Sweden)

Table 6
Thermophysical properties of materials for applications between 61 and 120 °C.

Material	Type	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m K)	Density (kg/m^3)
$NaAl(SO_4)_2{\cdot}10H_2O$	Inorganic (salt hydrate)	61 [13]	181 [13]	–	–
Bi–Cd–In	Inorganic eutectic	61 [13]	25 [13]	–	–
53% $Mg(NO_3)_2{\cdot}6H_2O$+	Inorganic eutectic	61[4,8,13]	148 [4,8,13]	–	1850
Paraffin C_{28}	Organic	61.6 [13]	253 [13]	–	–
Paraffin wax	Organic	64 [4,8]	173.6 [4,8]	0.167 (liquid)	790
			266	0.346 (solid)	216
Palmitic acid	Fatty acid	64 [1,4,6]	185.4 [1,4,6]	0.162 (liquid)	850 (liquid, 65 °C)
		61 [4,6,8]	203.4 [4,6,8]	0.159 (liquid)	847 (liquid)
		63 [4,8]	187 [4,8]	0.165 (solid)	989 (solid, 24 °C)
		69 [8]	202.5 [8]	0.172 (liquid)	848 (liquid)
		55 [13]	163 [13]		
NaOH	Inorganic (salt)	64.3 [4,8]	227.6 [4,8]	–	1690
		64.3 [13]	273 [13]		
50% CH_3CONH_2 + 50% $C_{17}H_{35}$ COOH	Organic eutectic	65 [13]	218 [13]	–	–
5% palmitic acid + 95% stearic acid	Organic mixture	65–68 [12]	209 [12]	–	–
Paraffin C_{30}	Organic	65.4 [13]	251 [13]	–	–
59% $Mg(NO_3)_2{\cdot}6H_2O$ + 41% $MgBr_2{\cdot}6H_2O$	Inorganic eutectic	66 [13]	168 [13]	–	–
Polyglycol E6000	Organic	66 [4,8]	190 [4,8]	–	1085 (liquid)
		55–66 [4]			1212 (solid)
Paraffin C_{21}–C_{50}	Organic	66–68 [4]	189 [4]	0.21	0.830 (liquid)
					0.930 (solid)
67.1% napthalene + 32.9% benzoic acid	Organic eutectic	67 [4,8,13]	123.4 [4,8,13]	0.136–0.282	–
$Na_2B_4O_7{\cdot}10H_2O$	Inorganic (salt hydrate)	68.1 [4,8]	–	–	–
Paraffin C_{31}	Organic	68 [13]	242 [13]	–	–
$Na_3PO_4{\cdot}12H_2O$	Inorganic (salt hydrate)	69 [4,8]		–	–
		65 [13]	190 [13]		
Stearic acid	Fatty acid	69 [1,4,8]	202.5 [1,4,8]		848 (liquid, 70 °C)
		60–61 [4,8]	186.5 [4,8]	0.172	965 (solid, 24 °C)
		69.4 [13]	199 [13]		
		70 [4,8]	203 [4,8]		
Paraffin C_{32}	Organic	69.5 [13]	170 [13]	–	–
Bi–Pb–In	Inorganic eutectic	70 [13]	29 [13]		
$Na_2P_2O_7{\cdot}10H_2O$	Inorganic (salt hydrate)	70 [4,8]	184 [4,8]	–	–
$LiCH_3COO{\cdot}2H_2O$	Inorganic (salt hydrate)	70 [13]	150 [13]	–	–
Biphenyl	Organic	71 [8]	119.2 [8]	–	991 (liquid)
					1166 (solid)
Biphenyl	Aromatic	71 [1]	119.2 [1]	–	991 (liquid, 73 °C)
					991 (solid 73 °C)
Bi–In	Inorganic eutectic	72 [13]	25 [13]	–	–
$Al(NO_3)_2{\cdot}9H_2O$	Inorganic (salt hydrate)	72 [13]	155 [13]	–	–
$Al(NO_3)_2{\cdot}9H_2O$	Inorganic (salt hydrate)	72 [13]	155 [13]	–	–
14% $LiNO_3$ + 86% $Mg(NO_3)_2{\cdot}6H_2O$	Inorganic eutectic	72 [13]	180 [13]	–	–
Paraffin C_{33}	Organic	73.9 [13]	268 [13]	–	–
Paraffin C_{34}	Organic	75.9 [13]	269 [13]	–	–
66.6% NH_2CONH_2 + 33.4% NH_4Br	Eutectic	76 [13]	151 [13]	–	–
$Mg(NO_3)_2{\cdot}6H_2O$ + 7% $MgCl_2{\cdot}6H_2O$	Inorganic eutectic	77.2–77.9 [12]	150.7 [12]	–	–
66.6% urea + 33.4% NH_4Br	Eutectic	76 [8]	161 [8]	–	–
$Ba(OH)_2{\cdot}8H_2O$	Inorganic (salt hydrate)	78 [1,4,6,8,13]	265–280 [1,4,6]	0.653 (liquid, 85.7 °C)	1937 (liquid, 84 °C)
				1.255(solid, 23 °C)	2180 (solid)
			265.7 [8]	0.653 (liquid, 85.7 °C)	1937 (liquid, 84 °C)
			267 [8]	0.678 (liquid, 98.2 °C)	2070 (solid, 24 °C)
			280 [8]	1.255 (solid, 23 °C)	2180 (solid)
			265 [13]		
Propionamide	Organic	79 [8]	168.2 [8]	–	–
$AlK(SO_4)_2{\cdot}12H_2O$	Inorganic (salt hydrate)	80 [8]	–	–	–
Naphthalene	Aromatic	80 [1,8]	147.7 [1,8]	0.132 (liquid, 83.8 °C)	976 (liquid, 84 °C)
				0.341 (solid, 49.9 °C)	1145 (solid, 20 °C)
25% $LiNO_3$ + 65% NH_4NO_3 + 10% $NaNO_3$	Inorganic eutectic	80.5 [13]	113 [13]	–	–
26.4% $LiNO_3$ + 58.7% NH_4NO_3 + 14.9% KNO_3	Inorganic eutectic	81.5 [13]	116 [13]	–	–
27% $LiNO_3$ + 68% NH_4NO_3 + 5% NH_4Cl	Inorganic eutectic	81.6 [13]	108 [13]	–	–
n-Tetracontane	Organic	82 [8]	–	–	–
Acetamide	Organic	82 [12]	263 [12]	–	1159
		81 [13]	241 [13]		
$Al_2(SO_4)_3{\cdot}18H_2O$	Inorganic (salt hydrate)	88 [8]	–	–	–
$Al(NO_3)_2{\cdot}8H_2O$	Inorganic (salt hydrate)	89 [8]	–	–	–
		89–90 [4,6]			
$Mg(NO_3)_2{\cdot}6H_2O$	Inorganic (salt hydrate)	89 [1,4]	162.8 [1,4]	0.490 (liquid, 95 °C)	1550 (liquid, 94 °C)
		89.3–89.9 [12]		0.611 (solid, 37 °C)	1636 (solid, 25 °C)
		89–90 [4,6,8]	149–163 [4,6,8]	0.669 (solid, 56 °C)	
		89.9 [13]	167 [13]		
$KAl(SO_4)_2{\cdot}12H_2O$	Inorganic (salt hydrate)	91 [13]	184 [13]	–	–
Xylitol	Organic	93–94.5 [12]	263.3 [12]	–	6.7–8.3
		94 [4]	263 [4]		
n-Pentacontane	Organic	95 [8]	–	–	779
$(NH_4)Al(SO_4){\cdot}6H_2O$	Inorganic (salt hydrate)	95 [8]	269 [8]	–	–

Table 6 (*Continued*)

Material	Type	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m K)	Density (kg/m^3)
Bi–Pb–tin	Inorganic eutectic	96 [13]	–	–	–
d-Sorbitol	Organic	96.7–97.7 [12]	185.0 [12]	–	1.5
		97 [4]			
$Na_2S\cdot(5/2)\,H_2O$	Inorganic (salt hydrate)	97.5 [8]	–	–	–
$KOH\cdot H_2O + KOH$	Inorganic (salt hydrate)	99 [8]	–	–	–
HDPE	Organic	100–150 [6,8]	200	–	–
Methyl fumarate	Organic	102 [8]	242	–	–
$CaBr_2\cdot 4H_2O$	Inorganic (salt hydrate)	110 [8]	–	–	–
Polyethylene C_nH_{2n+2} (n up to 100,000)	Organic	110–135 [8]	200 [8]	–	870–940 (solid)
$Al_2(SO_4)_3\cdot 12H_2O$	Inorganic (salt hydrate)	112 [8]	–	–	–
Quinone	Organic	115 [13]	171 [13]	–	–
$MgCl_2\cdot 6H_2O$	Inorganic (salt hydrate)	117 [1,4,6,8]	168.6 [1,8]	0.570 (liquid, 120 °C)	1450 (liquid,120 °C)
		116 [8]	165–169 [4,6]	0.694–0.704	1569 (solid, 20 °C)
		115 [8]	165 [8]	0.694 (solid, 90 °C)	1569 (solid, 20 °C)
		117 [13]	167 [13]	0.598 (liquid, 140 °C)	1442 (liquid, 78 °C)
				0.704 (solid 110 °C)	1569 (solid, 20 °C)
Erythritol	Organic	118 [6,8,12]	339.8 [6,8,12]	0.326	1300
		120 [4,12]	340 [4,12]	0.733	1480
Acetanilide	Organic	118.9 [12]	222	–	–

Table 7
Thermophysical properties of commercial products for cold storage (melting temperature up to 21 °C).

Product	Type	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m K)	Source
SN 33	Salt solution	−33 [8]	245 [8]	–	Cristopia
TH 31	Salt hydrate	−31 [8]	131 [8]	–	TEAP
SN 29	Salt solution	−29 [8]	233 [8]	–	Cristopia
SN 26	Salt solution	−26 [8]	168 [8]	–	Cristopia
TH 21	Salt hydrate	−21 [8]	222 [8]	–	TEAP
SN 21	Salt solution	−21 [8]	240 [8]	–	Cristopia
STL 21	Salt solution	−21 [8]	240 [8]	–	Mitsubishi Chemical
SN 18	Salt solution	−18 [8]	268 [8]	–	Cristopia
TH 16	Salt solution	−16 [8]	289 [8]	–	TEAP
STL 16	Salt solution	−16 [8]	–	–	Mitsubishi Chemical
SN 15	Salt solution	−15 [8]	311 [8]	–	Cristopia
SN 12	Salt solution	−12 [8]	306 [8]	–	Cristopia
STLN 10	Salt solution	−11 [8]	271 [8]	–	Mitsubishi Chemical
SN 10	Salt solution	−11 [8]	310 [8]	–	Cristopia
TH 10	Salt solution	−10 [8]	283 [8]	–	TEAP
STL 6	Salt solution	−6 [8]	284 [8]	–	Mitsubishi Chemical
SN 06	Salt solution	−6 [8]	284 [8]	–	Cristopia
TH 4	Salt solution	−4 [8]	386 [8]	–	TEAP
SLT 3	Salt solution	−3 [8]	328 [8]	–	Mitsubishi Chemical
SN 03	Salt solution	−3 [8]	328 [8]	–	Cristopia
Climsel C 7	Salt solution	7 [8]	130 [8]	–	Climator
RT 5	Paraffin	9 [12]	205 [12]	–	Rubitherm GmbH
RT 20	Paraffin	8 [12]	140 [12]	0.2	Rubitherm GmbH
Climsel C 15	Salt hydrate	15 [8]	130 [8]	–	Climator

Table 8
Thermophysical properties of commercial products for comfort applications in buildings (between 22 and 28 °C).

Product	Type	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m K)	Source
RT 20	Paraffin	22 [4,11]	172 [4,11]	0.88	Rubitherm GmbH
Climsel C 23	Salt hydrate	23 [8,11]	148 [8,11]	–	Climator
E23	Salt hydrate	23 [12]	155 [12]	0.43	EPS Ltd.
Climsel C 24	Salt hydrate	24 [4]	108 [4]	1.48	Climator
TH 24	Salt hydrate	24 [12]	45.5 [12]	0.8	TEAP
RT 26	Paraffin	25 [4,11]	131 [4,11]	0.88	Rubitherm GmbH
RT 25	Paraffin	26 [8,11]	232 [8,11]	–	Rubitherm GmbH
STL 27	Salt hydrate	27 [4,8,11]	213 [4,8,11]	1.09	Mitsubishi Chemical
S27	Salt hydrate	27 [11,8]	207 [11,8]	–	Cristopia
AC 27	Salt hydrate	27 [4]	207 [4]	1.47	Cristopia
RT 27	Paraffin	28 [4,11,12]	179 [4,11]	0.87	Rubitherm GmbH
			146 [12]	0.2	
RT 30	Paraffin	28 [8,11]	206 [8,11]	–	Rubitherm GmbH
E28	Salt hydrate	28 [12]	193 [12]	0.21	EPS Ltd.

Table 9
Thermophysical properties of commercial products for applications over 28 °C.

Product	Type	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m K)	Source
TH 29	Salt hydrate	29 [4,8,11,12]	188 [4,8,11,12]	1.09	TEAP
E30	Salt hydrate	30 [12]	201 [12]	0.48	EPS Ltd.
RT 32	Paraffin	31 [11]	130 [11]	–	Rubitherm GmbH
Climsel C32	Salt hydrate	32 [8,11]	212 [8,11]	–	Climator
E32	Salt hydrate	32 [12]	186 [12]	0.51	EPS Ltd.
A32	Aliphatic solution	32 [12]	145 [12]	0.21	EPS Ltd.
Suntech P116	Paraffin wax	43–56 [12]	266 [12]	0.24	Suntech
RT 40	Paraffin	43 [12]	181 [12]	–	Rubitherm GmbH
RT 42	Paraffin	43 [12]	150 [12]	0.2	Rubitherm GmbH
Paraffin 44	Paraffin	44 [12]	167 [12]	–	–
E44	Salt hydrate	44 [12]	105 [12]	0.43	EPS Ltd.
RT 41	Paraffin	43 [12]	150 [12]	0.2	Rubitherm GmbH
STL 47	Salt hydrate	47 [4,8]	221 [4,8]	1.34	Mitsubishi Chemical
Climsel C 48	–	48 [4,8]	227 [4,8]	1.36	Climator
E48	Salt hydrate	48 [12]	201 [12]	0.45	EPS Ltd.
E50	Salt hydrate	50 [12]	104 [12]	0.43	EPS Ltd.
STL 52	Salt hydrate	52 [4,8]	201 [4,8]	1.30	Mitsubishi Chemical
RT 52	Paraffin	52 [12]	138 [12]	0.2	Rubitherm GmbH
Paraffin 53	Paraffin	53 [12]	200 [12]	–	–
55 paraffin	Paraffin	52.5–53.7 [12]	182–189 [12]	–	Unicere
Paraffin 53	Paraffin	53 ± 2 [12]	164 [12]	2.13	–
Paraffin natural wax 53 (commercial grade)	Paraffin	53 ± 2 [12]	184 [12]	2.05	–
RT 50	Paraffin	54 [12]	195 [12]	–	Rubitherm GmbH
RT 54	Paraffin	55 [4]	179 [4]	0.90	Rubitherm GmbH
		55 [12]	148 [12]	0.2	Rubitherm GmbH
STL 55	Salt hydrate	55 [4,8]	242 [4,8]	1.29	Mitsubishi Chemical
Paraffin 56 (Russia)	Paraffin	56 ± 2 [12]	72–86 [12]	0.75	–
Paraffin 57 (Russia)	Paraffin	57 ± 2 [12]	98 [12]	0.70	–
E58	Salt hydrate	58 [12]	167 [12]	0.69	EPS Ltd.
TH 58	Salt hydrate	58 [4,8,12]	226 [4,8,12]	–	TEAP
Climsel C 58	Salt hydrate	58 [4,8]	259 [4,8]	1.46	Climator
RT 58	Paraffin	59 [12]	154 [12]	0.2	Rubitherm GmbH
RT 60	Paraffin	58–60 [12]	214 [12]	0.2	Rubitherm GmbH
Paraffin 63 (Russia)	Paraffin	63 ± 2 [12]	60 [12]	0.70	–
RT 65	Paraffin	64 [4,8,12]	173 [4]	0.91	Rubitherm GmbH
			207 [8]		
			154 [12]	0.2	
Paraffin 64	Paraffin	64 [12]	210 [12]	–	–
Climsel C 70	–	70 [4,8]	194 [4,8]	1.70	Climator
E71	Salt hydrate	71 [12]	123 [12]	0.51	EPS Ltd.
E72	Salt hydrate	72 [12]	140 [12]	0.58	EPS Ltd.
PCM 72	Salt hydrate	72 [8]	–	–	Merck Kga Λ
Paraffin natural wax 79 (Russia)	Paraffin	79 ± 2 [12]	80 [12]	0.63	–
RT 80	Paraffin	81 [12]	140 [12]	0.2	Rubitherm GmbH
		79 [8]	209 [8]		
PK 80	Paraffin	81 [12]	119 [12]	0.2	Rubitherm GmbH
E83	Salt hydrate	83 [12]	152 [12]	0.62	EPS Ltd.
Paraffin natural wax 84 (Russia)	Paraffin	84 ± 2 [12]	85 [12]	0.72	–
E89	Salt hydrate	89 [12]	163 [12]	0.67	EPS Ltd.
TH89	Salt hydrate	89 [8,12]	149 [8,12]	–	TEAP
RT 90	Paraffin	90 [8,12]	163 [12]	0.2	Rubitherm GmbH
			197 [8]		
RT 100	Paraffin	99 [12]	137 [12]	0.2	Rubitherm GmbH
Paraffin natural wax 106 (Russia)	Paraffin	106 ± 2 [12]	80 [12]	0.65	–
RT 110	Paraffin	112 [8]	213 [8]	–	Rubitherm GmbH
E117	Salt hydrate	117 [12]	169 [12]	0.70	EPS Ltd.

and Mitsubishi Chemical (Japan). The price of PCM varies in the 0.5–10 €/kg range [6].

4. Thermophysical properties

From the information compiled [4,8], the main characteristics required of phase change materials are those indicated in Table 10.

According to [1,4,6,11,13], the PCM to be used in the design of thermal storage system should have desirable thermophysical, kinetic and chemical properties:

- Thermophysical properties
  - Melting temperature in the desired operating temperature range: to assure storage and extraction of heat in an application with a fixed temperature range.
  - High latent heat of fusion per unit volume: to achieve high storage density compared to sensible storage.
  - High specific heat to provide additional significant sensible heat storage.
  - High thermal conductivity of both solid and liquid phases to assist the charging and discharging energy of the storage system.
  - Small volume change on phase transformation and small vapour pressure at operating temperature to reduce the containment problem.

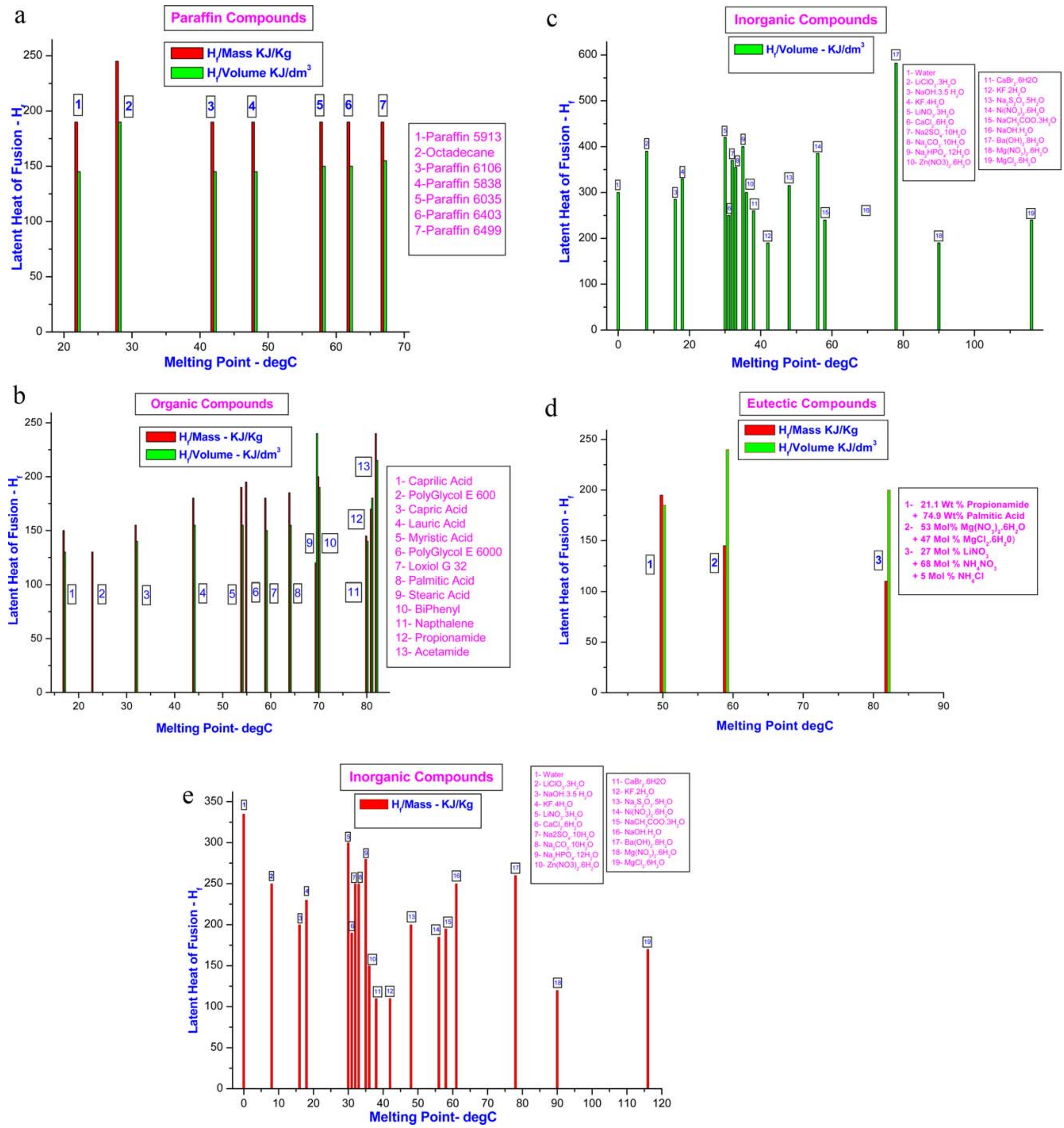


Fig. 3. Phase change materials listed in [9]. (a) Latent heat of melting of paraffin compounds. (b) Latent heat of melting of non-paraffin organic compounds. (c) Latent heat of melting/mass of inorganic compounds. (d) Latent heat of melting/volume of inorganic compounds. (e) Latent heat of melting of eutectic compounds.

Table 10
Important characteristics of energy storage materials [4,8].

Thermal properties	Physical properties	Chemical properties	Economic properties
Phase change temperature fitted to application	Low density variation	Stability No phase separation	Cheap and abundant
High change of enthalpy near temperature of use	High density	Compatibility with container materials	
High thermal conductivity in both liquid and solid phases (although not always)	Small or no undercooling	Non toxic, non flammable, non polluting	

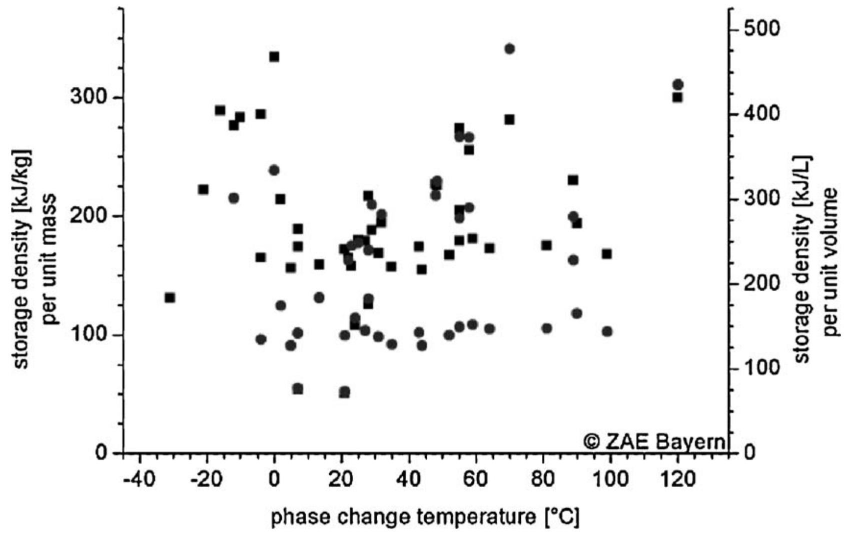


Fig. 4. Overview of meeting points and storage densities of commercial PCM: (●) in kJ/l and (■) in kJ/kg, as shown in [4,6].

- ◦ Congruent melting of the phase change material for a constant storage capacity of the material with each freezing/melting cycle.
- ◦ Reproducible phase change: to use the storage material many times (also called cycling stability).
- Nucleation and crystal growth
  - ◦ High nucleation rate to avoid super cooling of the liquid phase, and to assure that melting and solidification proceed at the same temperature.
  - ◦ High rate of crystal growth, so that the system can meet demand of heat recovery from the storage system.
- Chemical properties
  - ◦ Complete reversible freeze/melt cycle.
  - ◦ No degradation after a large number of freeze/melt cycle.
  - ◦ No corrosiveness to the construction materials.
  - ◦ Non-toxic, non-flammable and non-explosive material for safety: for environmental and safety reasons.
- Economics
  - ◦ Abundant.
  - ◦ Available.
  - ◦ Cost effective: to be competitive with other options for heat and cold storage.

Analysis techniques used to study phase change are mainly conventional calorimetry, differential scanning calorimetry (DSC) (Fig. 5) and differential thermal analysis (DTA) [4,8,13]. In [7] it is recommended to give the stored heat in fixed temperature intervals as shown in Fig. 6. Very detailed information on this topic can be found in [4].

When measuring the stored heat in a PCM using any kind of calorimeter, some important and general things have to be considered [7]:

- We need a representative sample size.

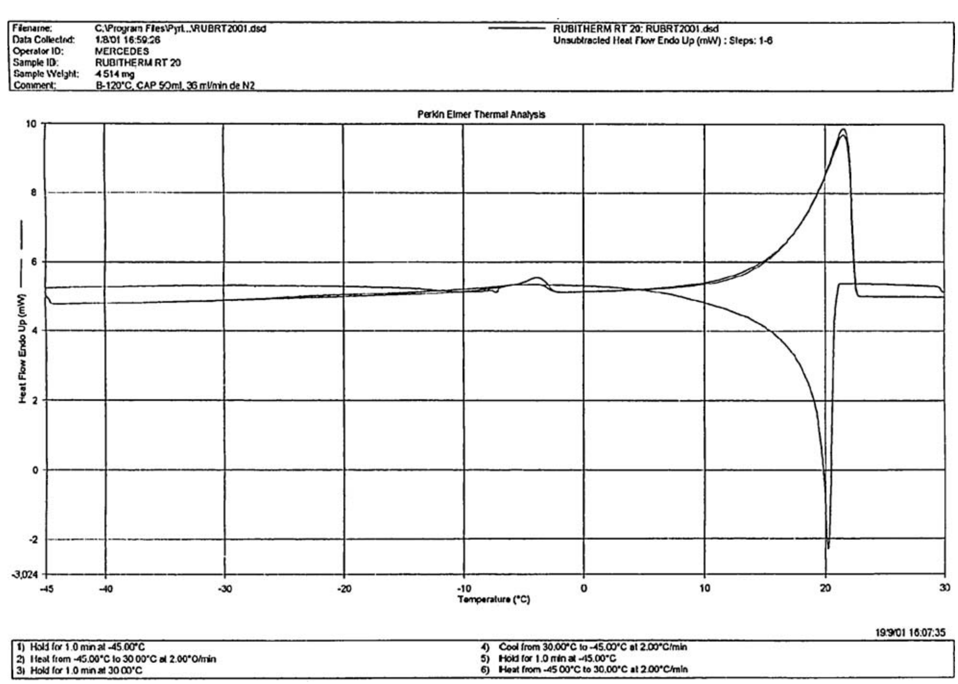


Fig. 5. DSC of paraffin RT20 [4].

T-Interval [°C]	stored heat [J/g]	stored heat [J/ml]
19,5 – 20,5	2,1	3,0
20,5 – 21,5	2,2	3,2
21,5 – 22,5	2,5	3,6
22,5 – 23,5	3,2	4,6
23,5 – 24,5	4,3	6,2
24,5 – 25,5	10,5	15,2
25,5 – 26,5	25,6	37,1
26,5 – 27,5	45,3	65,7
27,5 – 28,5	64,3	93,2
28,5 – 29,5	7,8	11,3
29,5 – 30,5	3,1	4,5
30,5 – 31,5	3,0	4,4
31,5 – 32,5	3,1	4,5
32,5 – 33,5	3,0	4,4
33,5 – 34,5	3,1	4,5
density at 34°C [g/ml]	1,45	

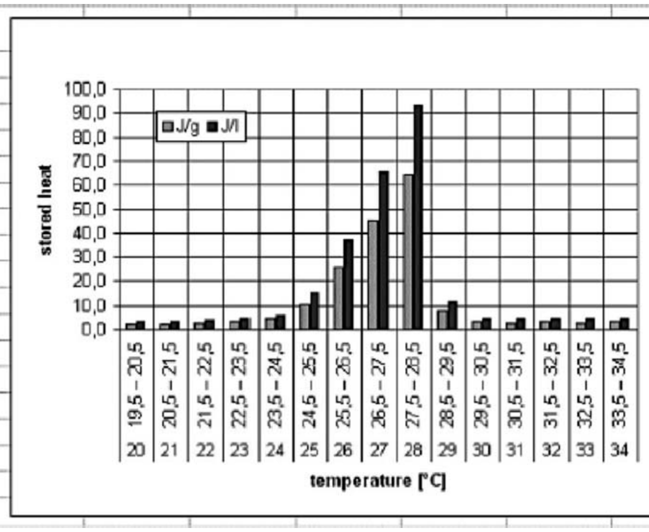


Fig. 6. Stored heat of a PCM in fixed temperature intervals [7].

- Sample preparation is very important and should be done correctly and repetitively.
- There should be a correct measurement of the temperature by the sensor.
- The heat flow should be correctly measurement.
- Thermodynamic equilibrium in the sample has to be ensured. Therefore the sample is isothermal, otherwise the heat flux cannot be attributed to the single temperature indicated at the sensor. Furthermore, the sample has to be in reaction equilibrium, so there should be no subcooling of the sample.

Another technique developed to analyse thermophysical properties of phase change materials is the T-history method [4,8]. Temperature–time graphs are drawn and properties evaluated for comparison with the graphs of the other known substances (usually pure water) used as reference. The results obtained are presented in the form of enthalpy–temperature curves (Fig. 7).

Another interesting property in phase change materials is thermal conductivity. Very little is published on this topic [4,8]. Much more information can be found on the enhancement of thermal conductivity in PCM, therefore it will be treated in another chapter of this review.

The density of a PCM is important because it affects its storage effectiveness per unit volume. Salt hydrates are generally more dense than paraffins and, hence, are even more effective on a per volume basis. The change of volume with the transition, which is in the order of 10%, could represent a minor problem [9].

5. Long term stability

The most important criteria that have limited the use of latent heat stores are the useful life of PCM–container systems and the number of cycles they can withstand without any degradation in their properties. The long term stability of the storage materials is due to two factors: poor stability of the materials properties and/or corrosion between the PCM and the container [1,4,7–9].

5.1. Stability of the PCM–container system

The development of PCM containers must be directed towards demonstration of physical and thermal stability, as the PCM must be able to undergo repetitive cycles of heating and cooling. The purpose of these thermal cycling tests is to determine whether these thermal exposures will result in migration of the PCM or may affect the thermal properties of the PCM [1,4].

5.2. Corrosion of the materials

The compatibility of PCM with other materials is important with respect to lifetime of the encapsulating material (or vessel) that contains the PCM, and the potential damage to the close environment in case of leakage of the encapsulation [6].

Common problems in materials compatibility with PCM are [6]:

- Corrosion of metals in contact with inorganic PCM.
- Stability loss of plastics in contact with organic PCM.

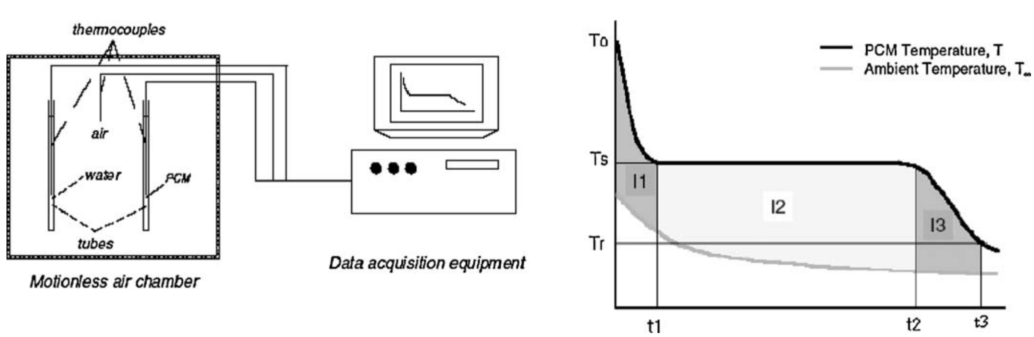


Fig. 7. T-history method: left – experimental set-up; right – temperature–time curves for PCM and ambient air [4].

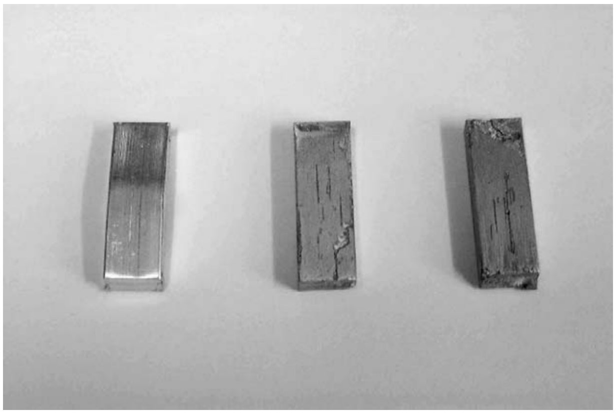


Fig. 8. Aluminum treated with a salt hydrate: from left to right – before treatment, after treatment, and after treatment in contact with graphite [4].

- Migration of liquid or gas through plastics that affect the performance of a contained organic or inorganic PCM and outside environment.

The reviews on phase change materials compile studies about corrosion of salt hydrates used as PCM on common metals [4,6,8] (Fig. 8).

5.3. Phase segregation and subcooling problems

The high storage density of salt hydrate materials is difficult to maintain and usually decreases with cycling. This is because most salt hydrates melt congruently with the formation of the lower salt hydrate, making the process irreversible and leading to the continuous decline in their storage efficiency (Fig. 9). This problem has also been studied by several researches [1,4,6,9]. Segregation can be prevented changing the properties of the salt hydrate with the addition of another material that can hinder the heavier phases to sink to the bottom. This can be achieved either with gelling or with thickening materials. Gelling means adding a cross-linked material (e.g., polymer) to the salt to create a three dimensional network that holds the salt hydrate together. Thickening means the addition of a material to the salt hydrate that increases the viscosity and hereby holds the salt hydrate together (Table 11).

Subcooling is another serious problem associated with all salt hydrates [4]. It appears when a salt hydrate starts to solidify at a temperature below its congealing temperature (Fig. 10). Several approximations have been studied to solve this problem. One is the use of salt hydrates in direct contact heat transfer between an immiscible heat transfer fluid and the salt hydrate solution. Another solution is the use of nucleators. An example of the work done with nucleators was published by [9].



Fig. 9. Segregation of a salt hydrate [4].

Potential nucleators are [6]:

- *Intrinsic nucleators*: particles of solid PCM. They have to be kept separately from the PCM as they would otherwise melt with the PCM and thereby become inactive.
- *Extrinsic nucleators*: often chemicals that show very similar crystal structure as the solid PCM. This usually means that they have similar melting temperatures as the PCM itself and thus become deactivated at temperatures very close to the melting point of the PCM itself.

6. Encapsulation of the materials

6.1. Macro and microencapsulated PCM

In almost all cases a PCM has to be encapsulated for technical use, as otherwise the liquid phase would be able to flow away from the location where it is applied. There are two principal means

Table 11
Subcooling range of thickened PCM with different nucleating agents [9].

PCM	Thickener	T_m (°C)	Nucleating agent (size, μm)	Subcooling (°C)	
				w/o nucleator	w/ nucleator
$Na_2SO_4 \cdot 10H_2O$	SAP	32	Borax (20 × 50 to 200 × 250)	15–18	3–4
$Na_2HPO_4 \cdot 12H_2O$	SAP	36	Borax (20 × 50 to 200 × 250)	20	6–9
			Carbon (1.5–6.7)		
			TiO_2 (2–200)		0–1
			Copper (1.5–2.5)		0–1
			Aluminum (8.5–20)		0.5–1
					3–10
$CH_3COONa \cdot 3H_2O$	CMC	46	Na_2SO_4		4–6
			SrO_4		0–2
			Carbon (1.5–6.7)		4–7
$Na_2S_2O_3 \cdot 5H_2O$	CMC	57	K_2SO_4		0–3
			$Na_2P_2O_7 \cdot 10H_2O$		0–2

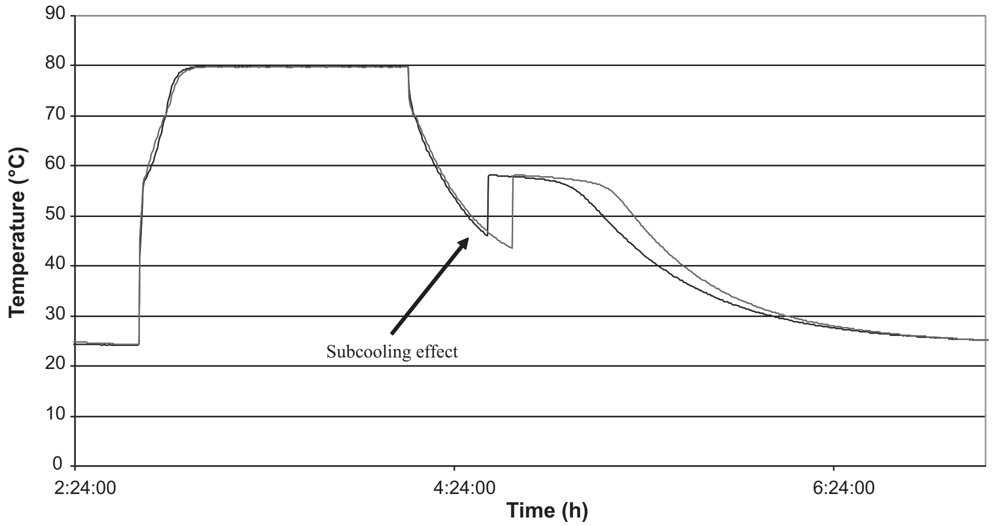


Fig. 10. Subcooling effect of a salt hydrate [4].

of encapsulation [10]. The first is microencapsulation, whereby small, spherical or rod-shaped particles are enclosed in a thin, high molecular weight polymeric film. The coated particles can then be incorporated in any matrix that is compatible with the encapsulating film. It follows that the film must be compatible with both the PCM and the matrix. The second containment method is macroencapsulation, which comprises the inclusion of PCM in some form of package such as tubes, pouches, spheres, panels or other receptacle. These containers can serve directly as heat exchangers or they can be incorporated in building products.

Macro encapsulation, which is encapsulation in containers usually larger than 1 cm in diameter, is the most common form of encapsulation.

Besides holding the liquid PCM and preventing changes of its composition through contact with the environment, macro encapsulation also:

- Improves material compatibility with the surrounding, through building a barrier.
- Improves handling of the PCM in a production.
- Reduces external volume changes, which is usually also a positive effect for an application.

Microencapsulation, which is encapsulation in particles smaller than 1 mm in diameter, is a recently developed new form of encapsulation for PCM. It can currently only be applied to hydrophobic PCM. Micro encapsulation serves the same purpose as mentioned above for macro encapsulation, but additionally:

- Improves heat transfer to the surrounding through its large surface to volume ratio.
- Improves cycling stability since phase separation is restricted to microscopic distances.

Composite materials are materials consisting of a PCM and at least one other material. The other material serves to improve at least one of the PCM properties. In most cases this is handling of the PCM, but compounds can also:

- Improve the cycling stability, again by microscopic structures that reduce phase separation.
- Improve heat transfer, through the addition of materials with large thermal conductivity as, for example, graphite.

The encapsulation of the PCM has developed interest in several researchers. Advantages and disadvantages of different geometries of PCM encapsulation with different materials and their compatibility were discussed [4,8,9].

For the use of PCM in buildings applications, PCM is included in an unsaturated polyester matrix or integrated with the building materials without encapsulation ("Shape-stabilised paraffin": 74% paraffin + 26% HDPE [high-density polyethylene]). Different methods have considered the means of PCM incorporation: direct incorporation, immersion and encapsulation. Fig. 11 shows an example of a network of polyacrylamide and PCM [9,15]. The PCM must be encapsulated so that it does not adversely affect the function of the construction material [4,8].

For many applications, PCM are microencapsulated, and this has been studied by several researchers [10] and developed by companies like BASF [4]. Nevertheless, the potential use of microencapsulated PCM in various thermal control applications is limited to some extent by their cost (Figs. 12 and 13 and Table 12).

Commercial companies have found different ways of encapsulating their PCM [1,4,6,12]. For example, Cristopia encapsulates the PCM in nodules (Fig. 14). The spherical nodules (*balls*) are blow moulded from a blend of polyolefins and filled with PCM. Rubitherm developed a heat storage granulate containing approximately 35 wt% of a phase change material (Fig. 15). Other companies have also commercial encapsulated products (Figs. 16–20).

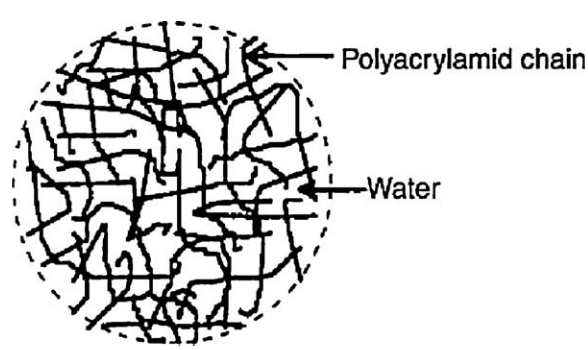


Fig. 11. The network of the polyacrylamide containing water used for low temperature phase change storage [9].

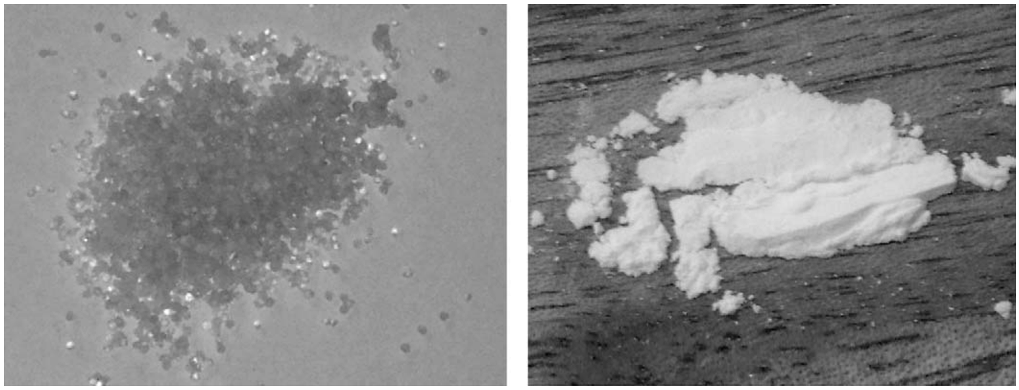


Fig. 12. Microencapsulated PCM: left – laboratory manufactured by copolymerization; right – commercialized by BASF [4].

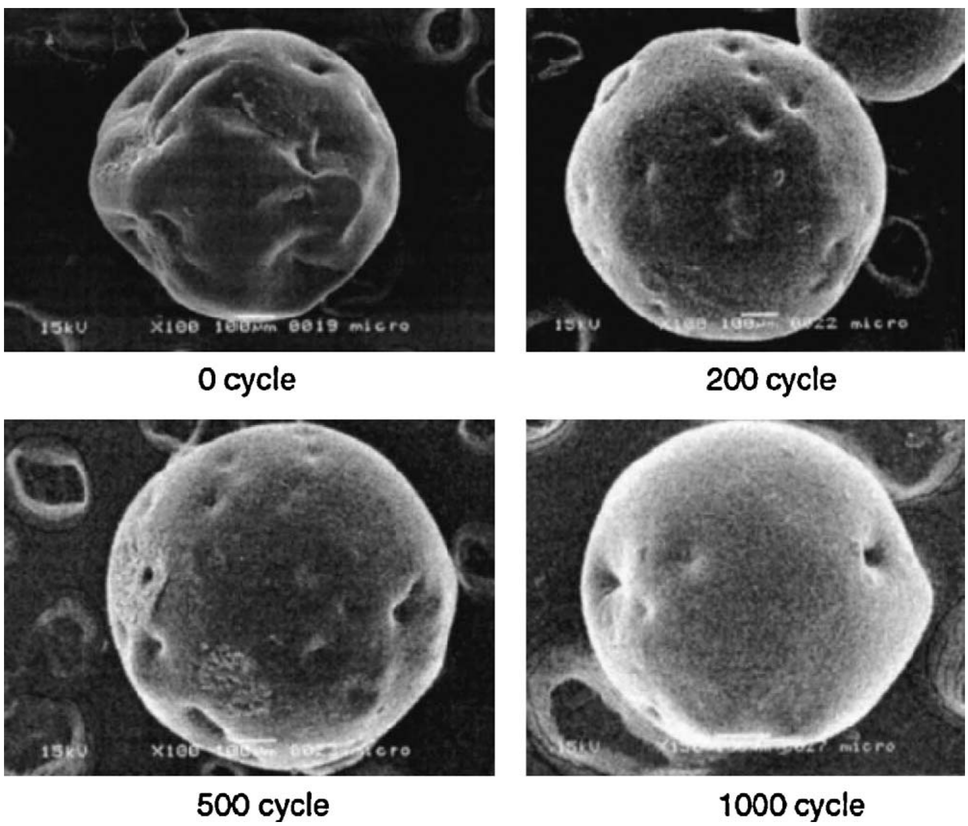


Fig. 13. Microencapsulated paraffin profile evaluated by SEM at different thermal cycles [10].

Table 12
Energy released and storage capacities for coacervated and spray dried microencapsulated PCM samples [10].

Samples	Coacervated samples			Spray dried samples		
Ratio	(2:1)	(1:1)	(1:2)	(2:1)	(1:1)	(1:2)
Energy stored (kJ/kg)	239.78	213.46	193.35	216.44	210.78	145.28
Energy released (kJ/kg)	234.05	224.31	196.38	221.51	211.66	148.32

6.2. Phase change material encapsulation in structures

During the last 20 years, several forms of bulk encapsulated PCM were marketed for active and passive solar applications, including direct gain. However, the surface area of most encapsulated commercial products was inadequate to deliver heat to the building after the PCM was melted by direct solar radiation. In contrast, the walls and ceilings of a building offer large areas for passive heat transfer within every zone of the building [10].

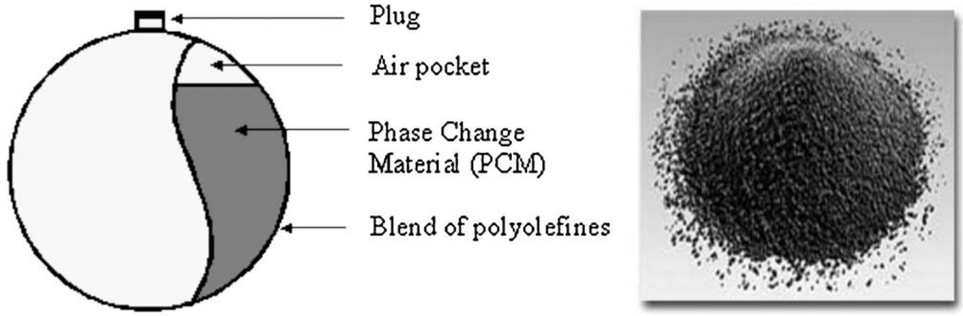


Fig. 14. Commercial encapsulated PCM: left – spherical nodule filled of PCM developed by Cristopia; right – granulated developed by Rubitherm [1,4].

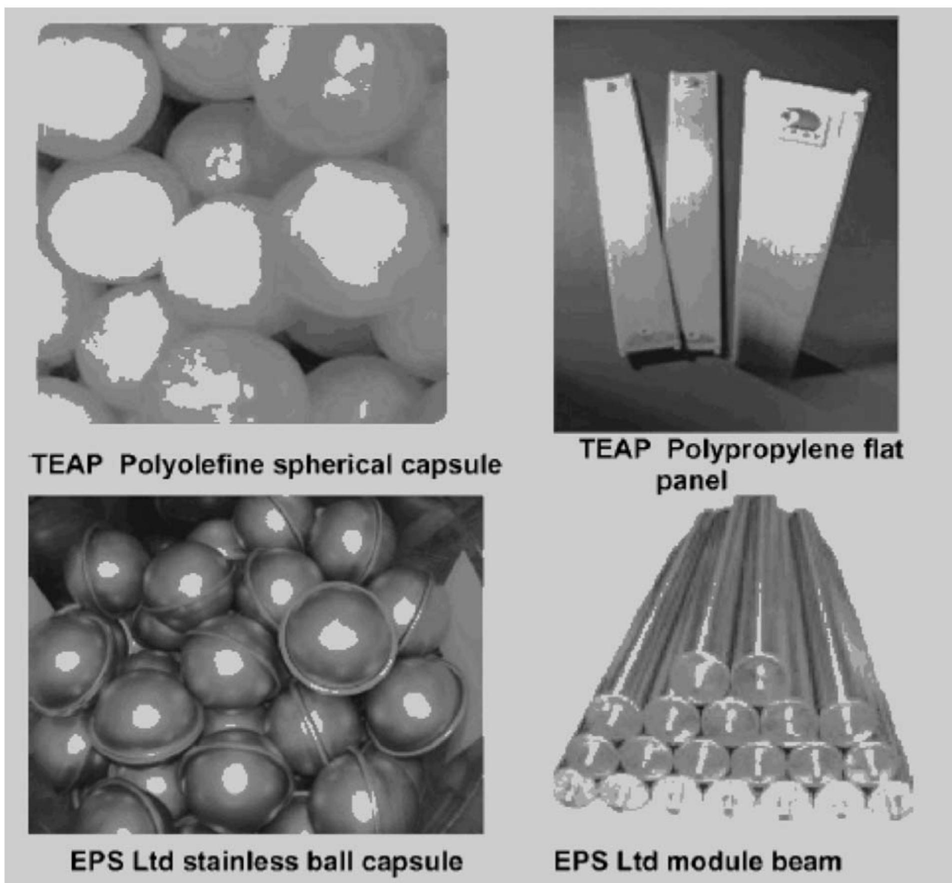


Fig. 15. Commercially manufactured phase change heat storage products [12].

Several workers have investigated methods for impregnating gypsum wallboard and other architectural materials with PCM [4,10]. Different types of PCM and their characteristics are described. The manufacturing techniques, thermal performance and applications of gypsum wallboard and concrete block, which have been impregnated with PCM are presented and discussed in [10,12] (Table 13).

Wallboards are cheap and widely used in a variety of applications, making them very suitable for PCM encapsulation [13]. However, the principles of latent heat storage can be applied to any

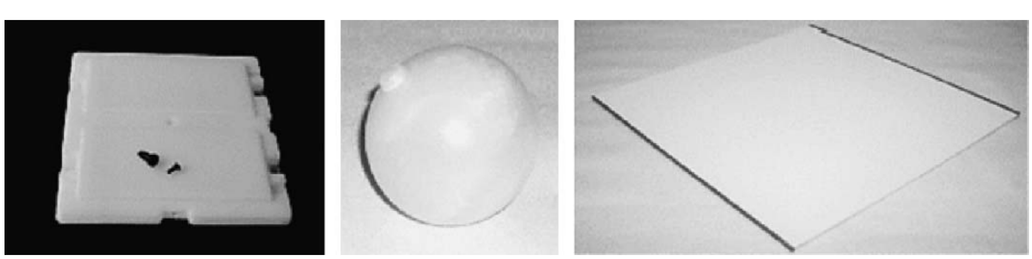


Fig. 16. Macroencapsulated PCM. From left to right: flat container (Kissmann/Germany), spheres and bar double plates (Dörken/Germany) [6].



Fig. 17. Macro encapsulation in bags. Left – from Climator/Sweden; right – from Dörken/Germany [6].

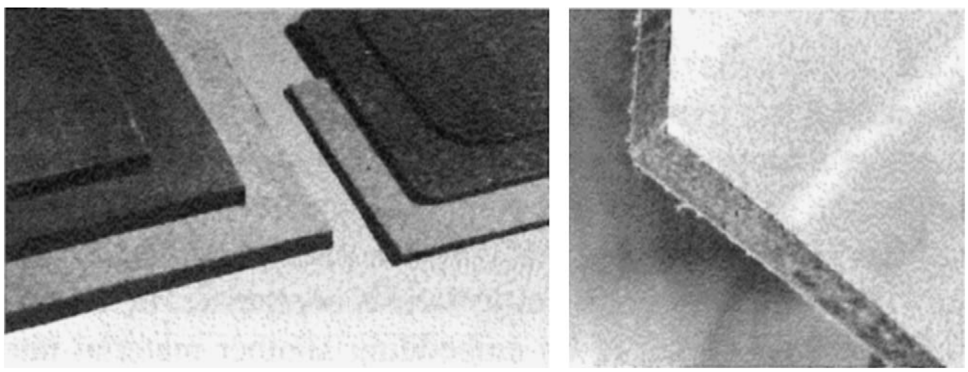


Fig. 18. Composites that come as boards or plates. Left – fibreboard FB (Rubitherm); right – DuPont panels [4].

Table 13
Commercially manufactured phase change storage tanks.

Volume (m^3)	External diameter (mm)	Total length (mm)	External surface area for insulation (m^2)	Connections inlet/outlet (mm)	Number of cradles	Empty weight (kg)	Heat transfer fluid volume (m^3)
Cristopia Energy Systems (Cristopia)							
2	950	2980	10	40	2	850	0.77
5	1250	4280	18	50	2	1250	1.94
10	1600	5240	29	80	2	1990	3.88
15	1900	5610	37	100	2	2900	5.82
20	1900	7400	47	125	3	3700	7.77
30	2200	8285	61	150	3	4700	11.64
50	2500	10,640	89	175	4	6900	19.40
70	3000	10,425	106	200	4	7300	27.16
100	3000	14,770	147	250	6	12,700	38.80
Environmental Process Systems Limited (EPS Ltd.)							
5	1250	3750	–	50	–	–	–
10	1600	4500	–	80	–	–	–
25	2000	8000	–	125	–	–	–
50	2500	10,000	–	150	–	–	–
75	3000	10,600	–	200	–	–	–
100	3000	11,100	–	250	–	–	–

Table 14
Calculated heat storage values for various PCM–block combinations as published in [10,12].

Heat storage values and temperature range	Block and PCM (% PCM in block)		
	A-BS (5.6%)	A-P (8.4%)	R-P (3.9%)
Temperature range (°C)	15–25	22–60	22–60
Storable sensible heat in blocks (kJ)	1428	5337	7451
Storable sensible heat in PCM (kJ)	233	1136	705
Storable latent heat in PCM (kJ)	977	2771	1718
Total storable heat (kJ)	2638	9244	9874
Total storable heat/storable sensible heat in blocks	1.9	1.7	1.3

Notes: specific heat of concrete block: 0.88 kJ/kg °C; specific heat of P: 2.04 kJ/kg °C; latent heat of BS: 101 kJ/kg (in 15–25 °C range); latent heat of P: 189 kJ/kg (in 22–60 °C range).



Fig. 19. Macro encapsulation in capsule stripes as produced by TEAP/Australia and Dörken/Germany for inorganic PCM.

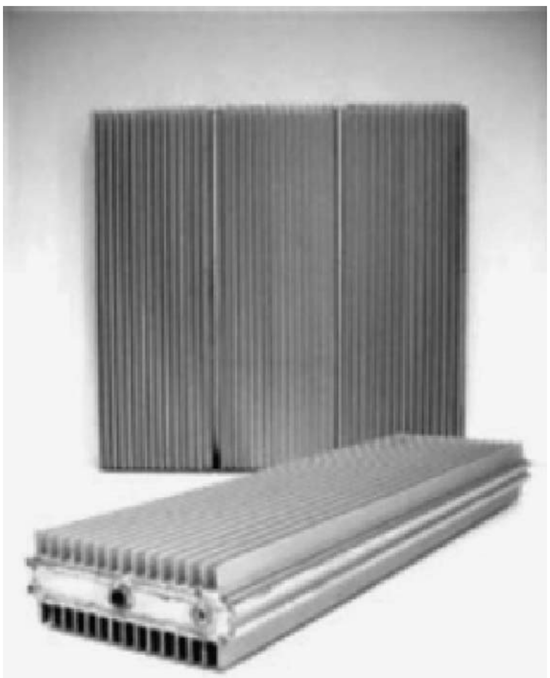


Fig. 20. Macro encapsulation in aluminum profiles with fins for improved heat transfer (Climator/Sweden) [6].

appropriate building materials. Processes where this PCM could be incorporated into plasterboard, either by post manufacturing incorporating liquid PCM into the pore space of the plasterboard or by addition in the wet stage of plasterboard manufacture, were successfully demonstrated. The first products are now available on the market (Fig. 21 and Table 14) [13].

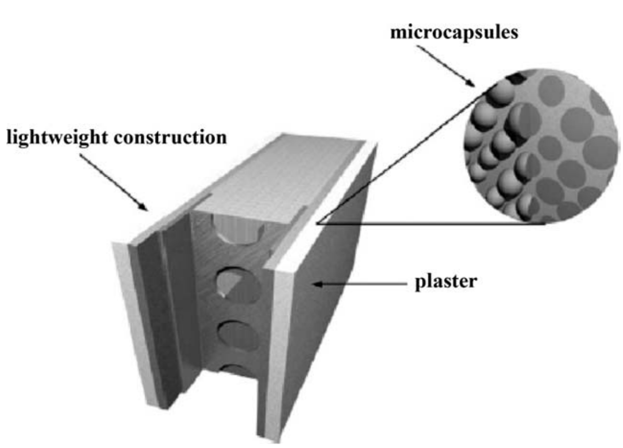


Fig. 21. Schematic view of a lightweight wall with microencapsulated PCM [13].



Fig. 22. Heat exchanger with finned tubes [4].

7. Fire retardation of PCM-treated construction materials

In recent years, stringent safety codes and flammability requirements have been imposed on building materials to protect these buildings from fire hazards. The following are some approaches that have been investigated and applied successfully in laboratory tests to fire retard PCM imbibed plasterboard [10]:

- Adding alternate non-flammable surface to the plasterboard (e.g., aluminum foil and rigid polyvinyl chloride film).
- Sequential treatment of plasterboard, first in PCM and then in an insoluble liquid fire retardant (e.g., Fyrol CEF). The insoluble fire retardant displaces part of the PCM and some remains on the surface, thus imparting self extinguishing characterization to the plasterboard.
- Using brominated hexadecane and octadecane as PCM. It is anticipated that when these halogenated PCM compounds are combined with antimony oxide in plasterboard, the product will be self extinguishing.
- Fire retardant surface coatings may be used to prevent effectively the wicking action of the plasterboard paper covers.

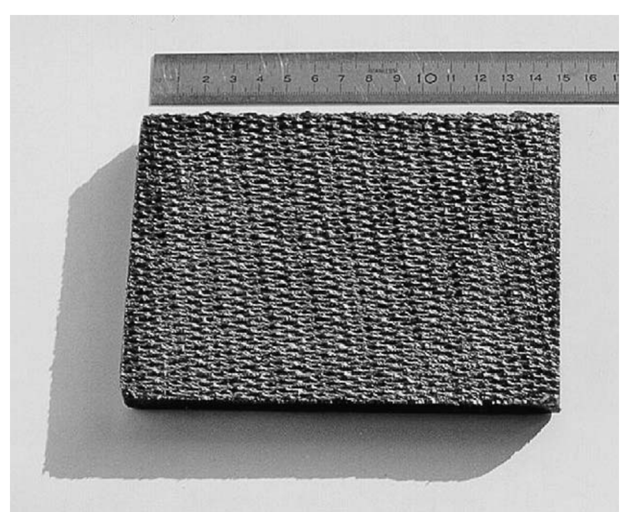


Fig. 23. Graphite-compound-material used to increase heat transfer (developed by ZAE Bayern and commercialized by SGL Technologies) [4].

8. Heat transfer enhancement

Heat transfer enhancement is of most importance in some application such as water tanks, but much less important when the PCM is integrated in building component for the envelope (gypsum boards, insulation materials, concrete, etc.).

There are several methods to enhance the heat transfer in a latent heat thermal store [4,6,8,9,12]. The use of finned tubes with different configurations has been proposed by various researchers (Fig. 22).

Several other heat transfer enhancement techniques have been reported [4,8]: improvement in solidification rate in molten salt dispersed with high conductivity particles, embedding the PCM in a metal matrix structure, and using thin aluminum plates filled with PCM. Also the use of graphite to enhance thermal conductivity of PCM in many ways has been studied [4,8] (Fig. 23).

9. Conclusions

The use of phase change materials (PCM) for thermal energy storage in buildings has been studied by many researchers, therefore, many products are available in the literature and some in the market. Technical problems found in the past in the use of such materials have been studied and different solutions have been presented, giving the user the opportunity to be sure that the systems designed would be successful. Nevertheless, research is still needed to find new more efficient and cheap materials, and to give better solutions to technical problems such as subcooling, segregation and materials compatibility.

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